REAL-TIME TESTBED SCPACECRAFT SIMULATION FOR THE DEEP SPACE ONE SPACECRAFT

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ABSTRACT

The Deep Space One (DS 1) Project is the first advanced technology validation mission that is part of the New Millennium Program sponsored by the National Aeronautics and Space Administration (NASA). The Jet Propulsion Laboratory (JPL) and it's industry partner for this endeavor, Spectrum Astro, Inc., are working together with a number of select integrated product development teams, and are tasked with the design, development, and in-flight validation of a chosen suite of advanced technologies.

To verify proper spacecraft function and performance prior to actual launch and in-flight operations, the spacecraft must be subjected to a battery of tests at the assembly, subsystem, and system levels. One facility where much of this testing will performed is the Flight System Testbed for Deep Space One (FST/DS 1). The FST/DS 1 is comprised of flight software test stations and a main integration and test station called the DS 1 Testbed. Considerable effort is being undertaken to develop a high fidelity spacecraft simulation to assist in the verification and validation of the avionics system on the DS 1 Testbed. A commercial product-derived spacecraft dynamics software simulation, inherited custom hardware models, and electrical ground support equipment consisting of both commercial and semi-custom components will be integrated to develop a fully operational spacecraft simulation.

This paper states the requirements for, describes the overall architecture of, and identifies the future work involved in developing the DS 1 Testbed spacecraft simulation.

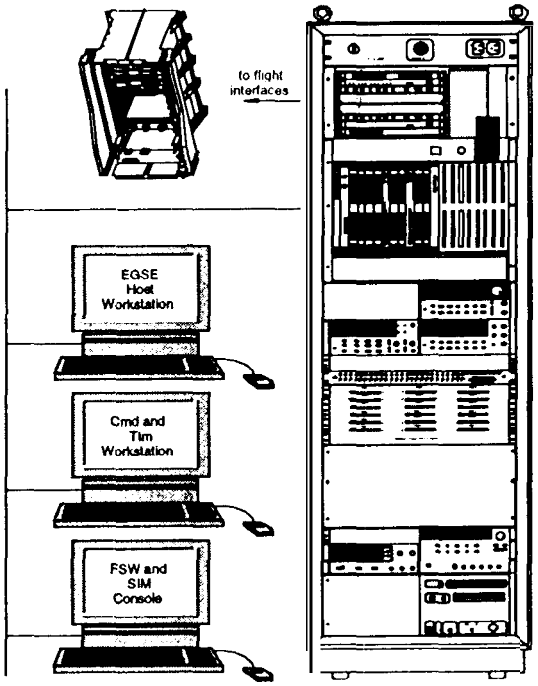
INTRODUCTION

The DS 1 Testbed (Figure 1) is comprised of 3 major elements: the Integrated Electronics Module (IEM), the Electronic Ground Support Equipment (EGSE) and the Spacecraft Simulation. Together the IEM, EGSE and Spacecraft Simulation provide a high-fidelity, closed-loop environment in which the DS 1 Flight Software (FSW) as well as electrical hardware interfaces are tested in preparation for spacecraft system testing at JPL.

The IEM is a VME (Versa Module Eurocard) chassis containing 13 cards which provide avionics functionality and interfaces for the DS 1 Spacecraft (see Table 1). The IEM of the DS 1 Testbed has an Engineering Model (EM) VME bus backplane and EM cards. Due to a lack of flight spare hardware on the DS 1 Program, EM hardware is treated like flight hardware in the DS 1 Testbed as well as in other developmental cycles of the program.

The EGSE, designed and built by Spectrum Astro Inc., provides the test interface to the IEM. MXI cards residing in VME chassis within the EGSE Signal Rack allow the testbed users to operate the EGSE Transition Modules, interfacing to each of the IEM boards, via NT Workstations (not shown in Figure I). The EGSE can stimulate IEM inputs as well as monitor the outputs of each of the IEM boards.

Integrated Electronics Module



EGSE Signal Rack

Figure 1- Main DS 1 Testbed Elements

Table 1. IEM Hardware List:

1. RAD6K microcomputer, inherited from the Mars Pathfinder project
2. EEPROM, Memory card
3. BTF - 13us Transfer Function (Intelligent 1553B Board)
4. UDL - Uplink & Downlink board
5. GPB - General Purpose Board
6. PCD - Pulse-Code Modulated Digital Board
7. PCA - Pulse-Code Modulated Analog Board
8. ACE - Attitude Control Electronics, provides interface to Miniature Integrated Camera Spectrometer (MICAS), Sun Sensor Assembly (SSA) & Inertial Measurement Unit (IMU)
9. GDE - Gimbal Drive Electronics
10. PCE - Propulsion Control Electronics
11. PDE - Propulsion Drive Electronics
12. IPC - IEM Power Converter
13. LPE/PASM - Low Power Electronics/Pulse-Activated Switching Module experiments

The Spacecraft Simulation software residing on a Heurikon HK68/V4F board is physically installed in the VME chassis of the EGSE Signal Rack. The Spacecraft Simulation provides high-fidelity hardware models and base-body dynamics to simulate the rest of the spacecraft in support of FSW functionality testing.

Various spacecraft hardware components that interface to the IEM will come to the DS 1 Testbed for integration. Depending on the availability of Flight Software at the time each of the external hardware components arrives, the component functionality will be verified to the extent possible in a closed-loop environment. Due to scheduling constraints and unavailability of spare hardware, some hardware components come to the Testbed for only a limited time prior to delivery to JPL System I&T. Additionally, these components may be scheduled into the Testbed prior to support of their functionality in Flight Software. In these cases, only the hardware interfaces of these components will be tested. Prior to their installation on the spacecraft.

The DS I Testbed facility itself is an approximately 500 square foot laboratory co-located with the FSW Integration & Test (I&T) testbed. It is a certified class 100K PPM (parts per million) clean room where both temperature and humidity levels are closely monitored. The facility is Electrostatic Discharge (ESD) certified and all test personnel working in the Testbed area are ESD certified as well.

REQUIREMENTS

A real time testbed environment which can demonstrate meeting the New Millennium Program DS 1 project objective by challenging the requirements of cheaper, faster, and better; a low-cost, rapid design, test and integration of the new advanced technologies.

The DS 1 Testbed will meet the end-to-end test environment needs for flight software design, development, test, integration and mission operation for DS 1. The flight software modules to be supported by this testbed environment include the attitude control system, optical navigation and flight system control.

The engineering model avionics board interfaces will be tested in this environment, including the uplink/downlink functions and ground data system interfaces.

The DS 1 Testbed environment will be integrated with the electronic ground support equipment (EGSE) for hardware-in-the-loop tests and system level integration. The purpose of the EGSE is to simulate the spacecraft and celestial flight environment in real-time, stimulate and monitor the testing of hardware and software in real-time, provide fault-injection capabilities, and to simulate subsystems that interface to the testbed environment when real flight hardware is unavailable.

At a latter date the testbed will provide flexibility and sufficient resources for verification and validation of the Autonomy Flight Software experiment.

There are several requirements that are specific to the Spacecraft Simulator. They can be grouped into two categories: those that support checkout of the flight software and those that support checkout of sequences.

FSW checkout will take several forms. Firstly, the simulator must allow for pairwise interface verification of flight software device managers and drivers with models of the hardware. This pairwise testing is performed to ensure that the data passed matches the specifications of the interface control documents for each hardware device. Secondly, the simulator needs to support functional verification of data passed back and forth. Having visibility into the state transitions and having limited error/fault insertion, the functional verification of the interfaces can be achieved. Lastly, the simulator needs to support functional verification of the algorithms that drive the interfaces. Using high fidelity spacecraft dynamics the simulator can close the loop on functional verification of algorithms which drive the interfaces (e.g., Attitude Control, Telecom, Power, etc.).

While support of flight software checkout often requires no coupling of hardware models within the simulator, sequence checkout requires a realistic system-level spacecraft model. This implies that the hardware models must interact with each other the same way the actual devices do. For example the star tracker model will not function unless it is powered by the power distribution unit mode]. Also, the simulator must provide an ephemeris model of the universe. This allows models like the star tracker, sun sensor and solar panels to have a knowledge of celestial bodies, including the Sun, Earth, stars and target bodies.

There are also certain things that the simulator will not do in order to reduce complexity and/or enhance computational performance. Firstly, flexible body dynamics will not be included to speed up computation time. It has been determined that the rigid body approximation of the flexible modes is sufficient to meet DS 1 Testbed testing requirements. Secondly, the simulator does not include complex modeling of telemetry link margin. At runtime a simple “No Link” message based on off-earth angle data and criterion is adequate.

ARCHITECTURE

The DS 1 Testbed Spacecraft Simulation (Figure **2) is** based upon the core capability developed for guidance and control algorithm verification and general flight software validation. The value-added by carrying this capability forward as part of the DS 1 Testbed configuration is the opportunity to test the flight software with as much flight hardware as possible, given the constraints imposed by cost, schedule, and technical feasibility.

This simulator has a reconfigurable architecture which allows it to be used in testbeds which range from software-only testbeds to hardware-in-the-loop testbeds. The model interfaces are specified so that as development progresses from software-only to hardware-in-the-loop testbeds, developers can unplug device models from the simulator to allow the real devices to be plugged in. The real hardware will interface to the remaining part of the simulation just as the models did.

There are four types of models integrated in the simulator: the spacecraft dynamics model , math models, device models and interface models. The spacecraft dynamics model was developed using the commercially - available SD/FAST Tool Set. Analysis of the actual spacecraft configuration shows that a simple four-body rigid model (i.e. no flexible modes) is a sufficiently accurate representation to ground validate functionality and certain performance characteristics. The spacecraft bus structure, the two solar array multi-panel 'wings', and the ion propulsion system engine constitute the four rigid bodies; connected to each other by Pin or U joints. Analysis also shows that the rigid-body model allows for a relatively long integration time step of 4 HZ while maintaining the required accuracy. Given these relatively 'loose' performance parameters, the Heurikon HK68/V4F (Motorola 68040 Processor), a commercially available VMEbus single board computer with a proven track record, was chosen as the hardware platform to run the simulation. The spacecraft dynamics represented by equations of motion responds to forces and torque's by accelerating, or rotating the spacecraft's inertial orientation. It also contains ephemeris information to know the location of celestial bodies.

Hardware models are used to replace spacecraft components that are either not available for long-term integration and use on the DS 1 Testbed or would be prohibitive for closed-loop testing given the constraints presented earlier. The logical and mathematical behavior of these devices are modeled as "device" and "math" models, respectively.

For devices that either require information about or have an impact on the spacecraft dynamic state, these devices are modeled as device models and math models. The device model is a coded representation of the device's state machine. For example, the ion propulsion thruster will transition from standby mode to thrusting mode as a result of receiving a specific 1553B command. This behavioral modeling is represented in the device model. The math model is the model which translates inputs to the spacecraft dynamics model. Continuing with the ion propulsion thruster example, the device model tells the math model the thruster is in thrusting mode. The math model then applies a thrust of a specified magnitude to the spacecraft dynamics model which causes an acceleration of the spacecraft. Some devices on the spacecraft do not impact the dynamics model . For example, the power distribution unit only handles power switching of the devices, and has no direct impact on the dynamics. It may power the thruster which will apply a force to the spacecraft, but it doesn't apply any forces or torques itself. Devices of this nature do not have math models. They only consist of a device model to represent the logical behavior. The device models represent fault behavior as well as nominal behavior. For example, if the Ion Propulsion System does not receive enough power from the SCARLET solar array model,

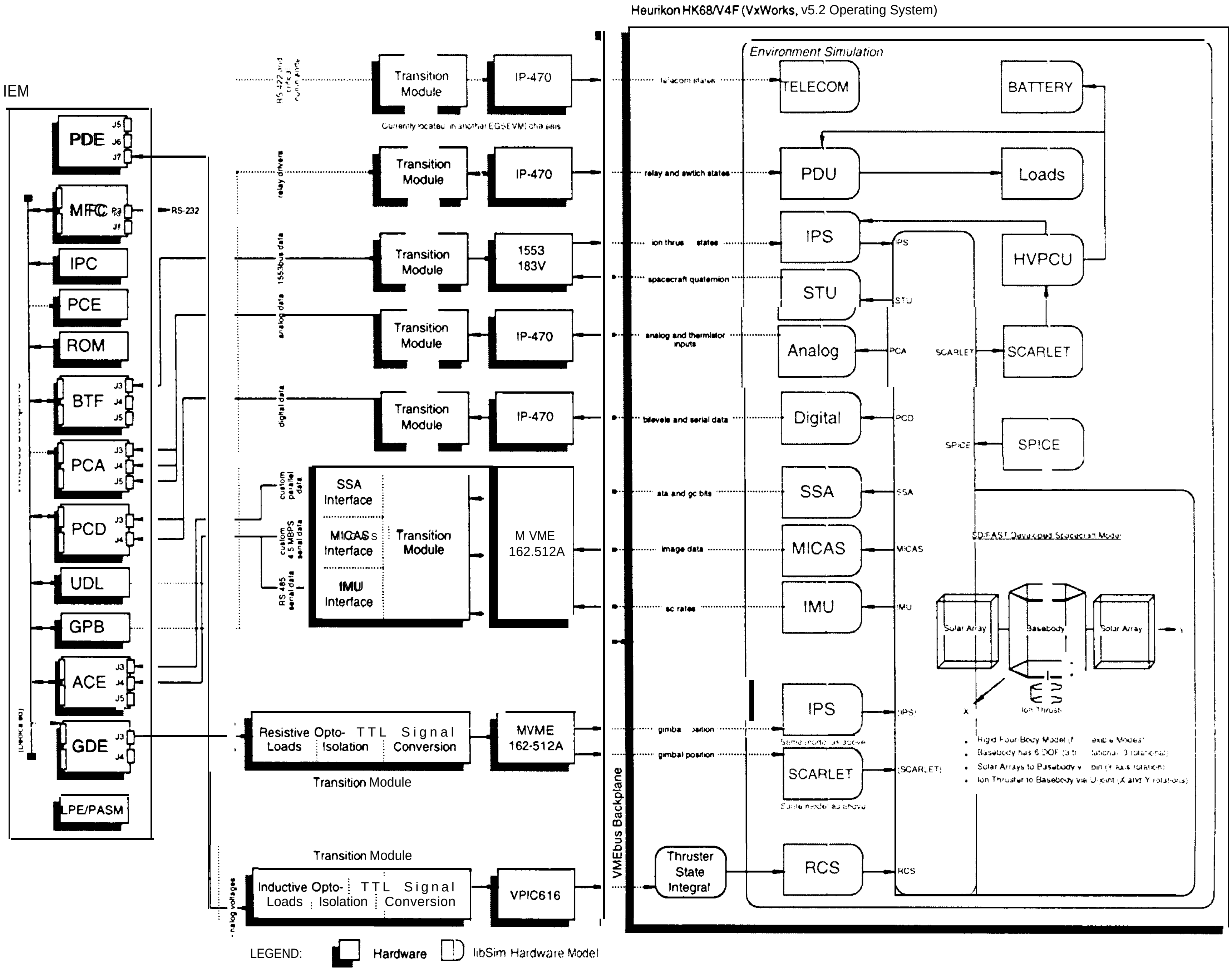


Figure 2 DS 1 Testbed Spacecraft Simulation Architecture

then the IPS will assume a fault condition exists and shut the engine off.

Finally, for every model that is replaced by hardware there is an interface model that allows the hardware to interface to the rest of the simulation.

All models interface to each other by passing data from their outputs to the inputs of other models each time the simulation clock ticks. The exchange of data is handled by a library of C functions called LibSim which was developed by the Autonomy Testbed Environment (ATBE) group at JPL. Using LibSim each model specifies inputs, outputs, and states. A "tie" file links one models output to another's input.

The entire set of models runs under a C main program which establishes the order of model execution. The main program also allows for viewing of model states, fault injection, checkpointing and time warping (jumping the clock forward in time) via a console.

Interfacing to hardware, which in the case of the DS 1 Testbed consists primarily of avionics contained within the integrated electronics module, is done through commercial and semi-custom electrical ground support equipment hardware. The most simple of these is the 1P (Industry Pack) carrier and the transition module. This configuration is valid for interfaces associated with the general purpose board, pulse code modulation digital card, etc. . . The 1P carrier is essentially an 1/0 card that is compatible with the VMEbus Standard. The transition module provides the actual interface to the flight hardware, and as such, provides the necessary opto-isolation and differential to single-ended TTL signal conversion required by the 1P carrier. A derivative of this is the interface for the propulsion drive electronics. The front end of the transition module consists of inductive loads that simulate the RCS thruster valves. The next step involves replacing the 1P carrier with a single board computer for more complex interfaces, such as the attitude control electronics. Finally, MIL-STD- 1553 bus interfaces, such as the Bus transfer function, require the use of a commercial Bus controller and monitor.

The DS 1 Testbed Spacecraft Simulation takes advantage of previously built capabilities, semi-custom and commercial components to reduce cost and complexity without giving up on required fidelity for functional and performance validation of spacecraft capabilities.

STATUS AND FUTURE WORK

The Spacecraft Simulator currently consists of mostly software models of the devices. However, these models do communicate using realistic interfaces. Models of 1553 remote terminals communicate over an actual 1553 data bus and models which communicate over VME read and write data to the VME addresses that the flight software managers is expecting. Thus, the first step towards integrating flight hardware was establishing proper communication over flight-like data buses.

The next phase of integration will include the extraction of device models for which we have IEM hardware. Such models will be replaced by the flight hardware, a corresponding transition module and a new interface model. In the case of hardware that was represented by and device model and a math model, only the device model portion is replaced. The transition module interfaces to the interface model which serves two functions. Firstly, it provides an intermediate location to insert errors in order to test fault protection response. Secondly, it communicates with the math model in order to maintain closed-loop communication with the spacecraft dynamics model.

In addition to replacing models with hardware, considerable modeling of devices remains to be done. Recall that only IEM hardware will replace models. Most modeling work that remains includes simulation of Attitude Control devices and the science experiments. Simple models which simulate the interfaces exist for many of these devices. This may be sufficient for testing the flight software interaction with the science experiments. In most cases, the flight software is only concerned with proper communication across the bus. However, full state representations which include fault modes is more critical for the Attitude Control devices. This is still being worked.

Checkpointing and time warping are also being worked. Both of these features will greatly facilitate testing by being able to save and resume a simulation or jump forward in time during a test. Both features also require flight software development work in order for the simulator and the flight software to be properly synchronized.

The final stage of simulation development work is code optimization. Actually, this is part of an iterative process whereby we regularly evaluate the CPU margin to ensure that the simulation has sufficient time to complete all processes and meet the real-time requirements.

The DS 1 Testbed will be used to support the formal system level Integration and Test program on the DS 1 Spacecraft as well as post-launch mission operations. The testing involves exercising select modes in flight-like scenarios as well as sequence verification activities before and after launch.

JPL and AMES Research Center are partners in the development of Remote Agent spacecraft autonomy technology. The DS 1 Testbed will support the Remote Agent experiment validation activities, with some use of the DS 1 Testbed before launch, but most occurring post-launch.

CONCLUSION

The development of the DS 1 Testbed Spacecraft Simulation is taking advantage of existing in-house software, and capitalizing on the work done in other areas such as the dynamics engine developed through SD/FAST, a commercially-available tool. This design enables easier maintainability and usability. The simulation architecture is modular in design, and the simulation interfaces are highly configurable to allow swapping in and out of hardware as needed. The core simulation is being used in a number of areas and being adapted for use on the DS 1 Testbed. This simulation task can support the evolution in model functionality and fidelity, and enables the low-cost, test and integration of the DS 1 spacecraft capabilities.

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